

Forecasting Coastal Optical Properties using Ocean Color and Coastal Circulation Models

R. A. Arnone^a, B. Casey^b, D. Ko^a, P. Flynn^a, L. Carrolo^a, S. Ladner^b

^aNaval Research Laboratory, Stennis Space Center, MS 39529-5004

^bPlanning Systems Incorporated, Space Center, MS 39529-5004

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ABSTRACT

Coupling the 3-d ocean optical imagery with 3-d circulation models provides a new capability to understand coastal processes. Particle distribution derived from ocean color optical properties were coupled with numerical circulation models to determine a 24 hour forecast of particle concentrations.

A 3-d particle concentration field for the coastal ocean was created by extending the surface satellite bio-optical properties vertically by parameterizing an exponential Gaussian depth profile. The shape of the vertical particle profile was constrained by 1) the depth of the 1% light level 2) the mixed layer depth 3) the intensity of the layer stratification 4) and subsurface current field and the surface bio-optical properties. These properties were obtained from MODIS ocean optical products (phytoplankton absorption and backscattering) and the Intra-America Sea Nowcast Forecast System - Naval Coastal Ocean Model.

The 3-d particle distribution was imbedded into a 3-d circulation model and the particles advected hourly using forecast 3-d current. The particles were diffused, dispersed and differentially settled during the advection processes. Following the 24 hour advection, the resultant particle distribution were accumulated into 1 km spatial grid and vertically to a 1 attenuation length (satellite penetration depth) and the forecast ocean color backscattering image determined. The forecast image was compared with the next day ocean color backscattering image to define the error budget.

The ocean color particle tracking, defines fine spatial scales processes such as local upwelling and downwelling, which are essential in understanding the coupling of physical and bio-optical processes. The methods provide new capability for characterizing how subsurface particles layers change in response to cross and along shelf exchange processes. Results show methods to forecast satellite optical properties in coastal areas and examine how sequential MODIS imagery of the particle scattering is related to particle transport and physical processes

Keywords: Ocean Optics, Satellites, Ocean Color, ocean models

1. INTRODUCTION

Remote sensing of ocean color is used to characterize and monitor coastal processes. Our capability to exploit ocean color to retrieve the near surface bio-optical properties is limited to within the upper first attenuation length. The vertical variability of the bio-optical properties changes significantly in response to both biological and physical processes. These subsurface biological processes are important to understand the optical layers such as the location and intensity of the chlorophyll maximum and bottom resuspension layers. These layers influence the shape of the vertical profile which is tied to the near surface observation of surface satellite imagery¹.

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14. ABSTRACT Coupling the 3-D ocean optical imagery with 3-D circulation models provides a new capability to understand coastal processes. Particle distribution derived from ocean color optical properties were coupled with numerical circulation models to determine a 24 hour forecast of particle concentrations. A 3-D particle concentration field for the coastal ocean was created by extending the surface satellite bio-optical properties vertically by parameterizing an expediential Gaussian depth profile. The shape of the vertical particle profile was constrained by 1) the depth of the 1% light level 2) the mixed layer depth 3) the intensity of the layer stratification and 4) subsurface current field and the surface bio-optical properties were obtained by MODAS ocean optical products (phytoplankton absorption and backscattering) and the Intra-Americas Sea Nowcast Forecast System- Naval Coastal Ocean Model....					
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New methods are required to extend the near surface remote sensing to characterize the subsurface properties. These capabilities are important for understanding the total exchange processes across front zones and the transport studies from coastal to open ocean waters.

Remote sensing ocean color provides a unique capability to monitor the bio-optical conditions within the coastal zone by providing a 'Nowcast' of the current conditions. However, coastal managers require a capability to "forecast" the bio-optical conditions to be used for decision making. Improved methods are required to forecast the 24 hour surface bio-optical properties and can be accomplished by combining remote sensing products with forecast circulation models ^{2,3}.

The near surface particle distribution field can be retrieved from the remote sensed backscattering intensity ^{4,5}. This particle field is coupled with modeled currents to advect the particle field to provide a 24 hour forecast. The particle field distribution from the satellite backscattering imagery provide the initial "seed" field for the model currents as a representation of the spatial concentrations and distribution of particles. The model currents, transports these particle trajectory on hourly time steps to determine the 24 particle concentration. The particles are then accumulated into 1 km bins representing similar resolution as ocean color satellites and converted back to a backscattering coefficient. This particle tracking assumes particle settling and diffusion and *only* particle "seeding" at the surface. (The previous 3-d vertical bio-optical model will be used to generate a 3-d particle "seed" for the circulation in the near future.) Biological processes such as plankton growth and decay as not included in this approach. This is an initial effort to estimate the particle forecast to assess how much of the variability can be assessed based on simply advection processes. The forecast capability of the particle field provides a useful tool to assess the changing coastal conditions and provide decision making for the future.

2. DETERMINING THE VERTICAL 3-D OPTICAL VARIABILITY

The extensions of the satellite optical properties were performed by characterizing the shape of the vertical as a Gaussian^{1,2}. The vertical profiles of bio-optical profiles such as the chlorophyll maximum layer have been shown to be well defined using a Gaussian shape ⁶. We developed new methods to provide constraints on the profile shape which are controlled by the link between the mixed layer depth (MLD), intensity of the mixed layer (IMLD) and the 1 percent light level. These constraints were determined by analyses of many profiles of temperature, salinity, fluorescence and backscattering in a wide variety of open and coastal waters representing a variety of water types and process. In this study, the physical properties of MLD and IMLD are provided through the physical circulation model and the subsurface light fields of the 1 % light level are estimated using the surface satellite inherent optical properties⁷. These shape parameters of the Gaussian are then linked to the surface satellite surface chlorophyll¹. The vertical Gaussian shape is defined by:

$$b(z) = b_0 e^{(k b_0 z)} + \frac{h}{\sigma(2\pi)^{0.5}} e^{-\frac{(z-z_m)^2}{2\sigma^2}} \quad (1)$$

where parameters are defined in Figure 1 and (k) is the decay of the background chlorophyll. Adjustment of these parameters allows various vertical shapes to be defined. The shape of the profiles is coupled to the surface chlorophyll by setting the integration of the 1st optical depth of this shape to the satellite chlorophyll value.

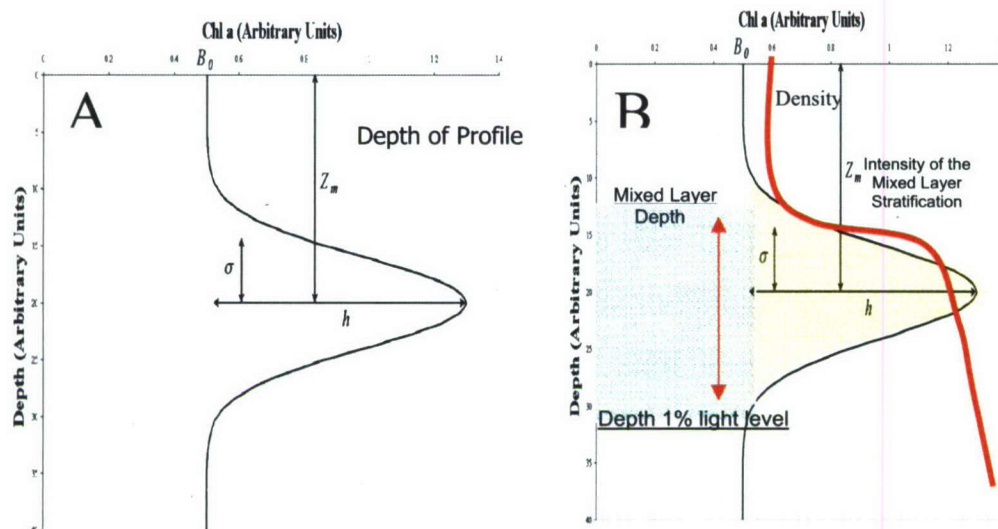


Figure 1 – A. Shape of the Bio-optical profile identifying the components (Z_m, σ, h, B_0). B. The location of the optical layer constrained between the mixed layer depth from the density profile and the 1% light level. The intensity of density stratification defines the height or elevation of the Gaussian peak.

The parameters which are used to constraint this profile shape are obtained from both the surface satellite optics and the Navy Coastal Ocean Model (NCOM)⁸. The density field from NCOC is used to determine the MLD and the IMLD. NCOC is a 41 layer model currently used for Navy operations. The model is forced with COAMPS winds and obtains boundary conditions from the “Global NCOC”. These models assimilate the sea surface height fields from satellite altimeter and sea surface temperature from AVHRR⁹. The vertical density field from NCOC is used to estimate the MLD and the density derivative is used to estimate the degree of stratification or the IMLD. Figure 1b illustrates how the location of the optical layer is linked to the MLD and the IMLD. NCOC examples of the MLD and the IMLD are shown below.

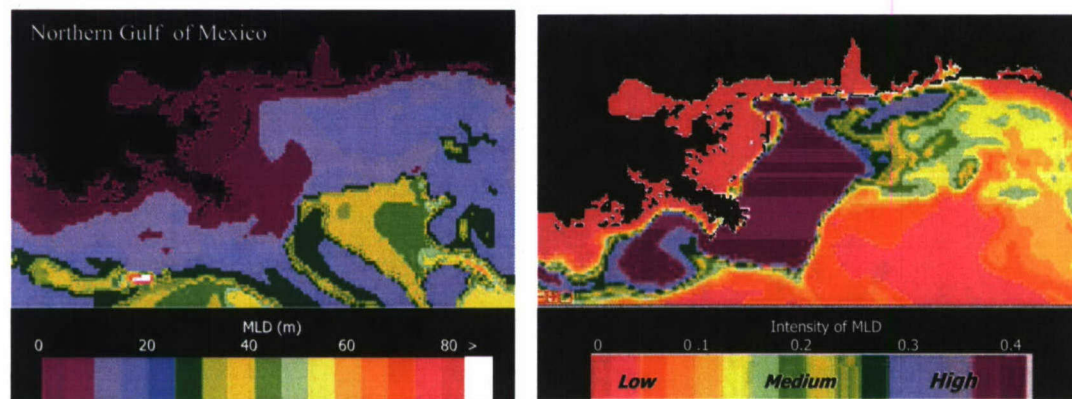


Figure 2. Output from the NCOC vertical density profile is used to determine the Mixed layer depth and the intensity of the mixed layer depth. These parameters are linked with the vertical bio-optical properties. Example of the NCOC for the Mississippi River discharge is shown.

The IMLD indicate the degree of stratification and this controls the sharpness of the chlorophyll layer (σ , h). The 1 percent light level depth (PD) was computed using the satellite retrieved absorption and backscattering properties as described by^{7,10}.

The depth of the chlorophyll max (Zm) is constrained between the MLD and the PD using the equation:

$$Z_m = f (MLD + (PD - MLD) * e^{(-C1 * IMLD)}) \quad (2)$$

Similarly the Chlorophyll Maximum for the profiles is estimated by:

$$Chl\text{-}Max = f (MLD / PD * C2 / SfcChl) \quad (3)$$

The Gaussian Spread is estimated using:

$$\sigma = f ((C3 - 1) * \exp(-C4 * IMLD) + 1) \quad (4)$$

The coefficients **C1**, **C2**, **C3**, and **C4** were determined through optimization based on insitu data stations of the vertical density profiles and the chlorophyll profiles. The spatial and temporal variability of these coefficients is an active area of research which includes characterizing the response of these coefficients to different processes which include bio-optical and physical coupling.

The results of the 3-d model are shown by comparison with insitu observations of fluorescence and density.

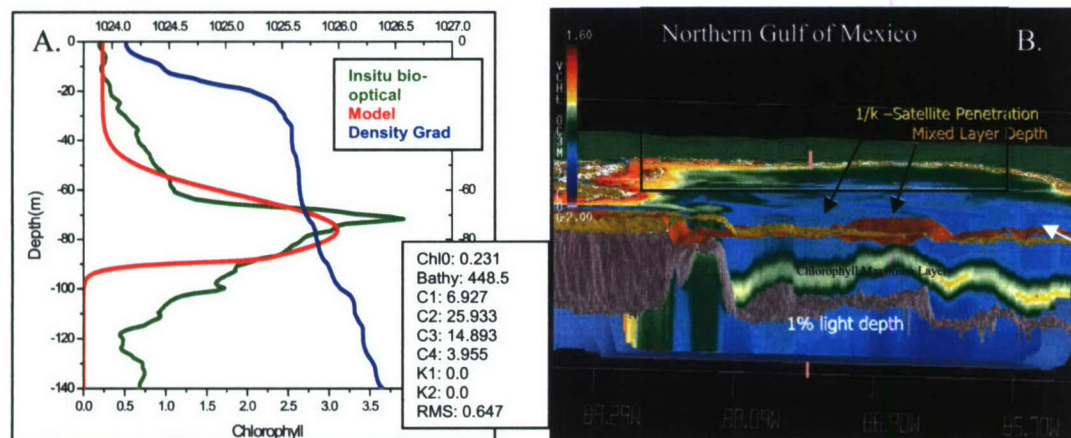


Figure 3: A. The results of the 3-d model are shown in comparison with insitu density and the fluorescence profile. The profile shape is coupled with the surface satellite chlorophyll to the first optical depth. The coefficients for this profile are shown for C1, C2, C3, and C4.

B. 3-d chlorophyll volume of the Northern Gulf of Mexico. The surface MODIS chlorophyll is extended vertically using the 3-d model by combining with the NCOM physical properties. Mississippi River discharge is on the left. Note layers.

3. FORECASTING THE OPTICAL ENVIRONMENT

The coupling of remote with numerical forecast models permits the capability to forecast the ocean optical environment. The ocean color imagery from MODIS has been used to determine the near surface backscattering coefficient (bb555). The bb555 is directly related to the number of particles in the surface waters in addition to the particle size, composition and index of refraction^{5,11}. We assume a linear relationship between the particle concentration and the bb555 to estimate the surface particle numbers in a satellite image. This surface particle field is characterized as the "seed" field of the particle's spatial distribution of surface waters. This "seed" field is inserted into the surface circulation field of the NCOM model and the particles are dispersed and settled at hourly time sets based on the model hour forecast field for a period of 24 hours. Note that the satellite particle field represents only near surface layer and not the 3-d particle field (in its present configuration.)

Following the 25 hour particle dispersion, the particles are accumulated into 1 km regional pixels and transformed back into the bb555. This resulting 25 hour forecast represents the forecast backscattering MODIS image which can be compared with the next day MODIS bb555 image. The difference fields represent the errors associated with 1) model errors in circulation 2) errors in particle dispersion 3) non-conservative particle interaction including settling and growth, accumulation etc. 4) particle upwelling and downwelling.

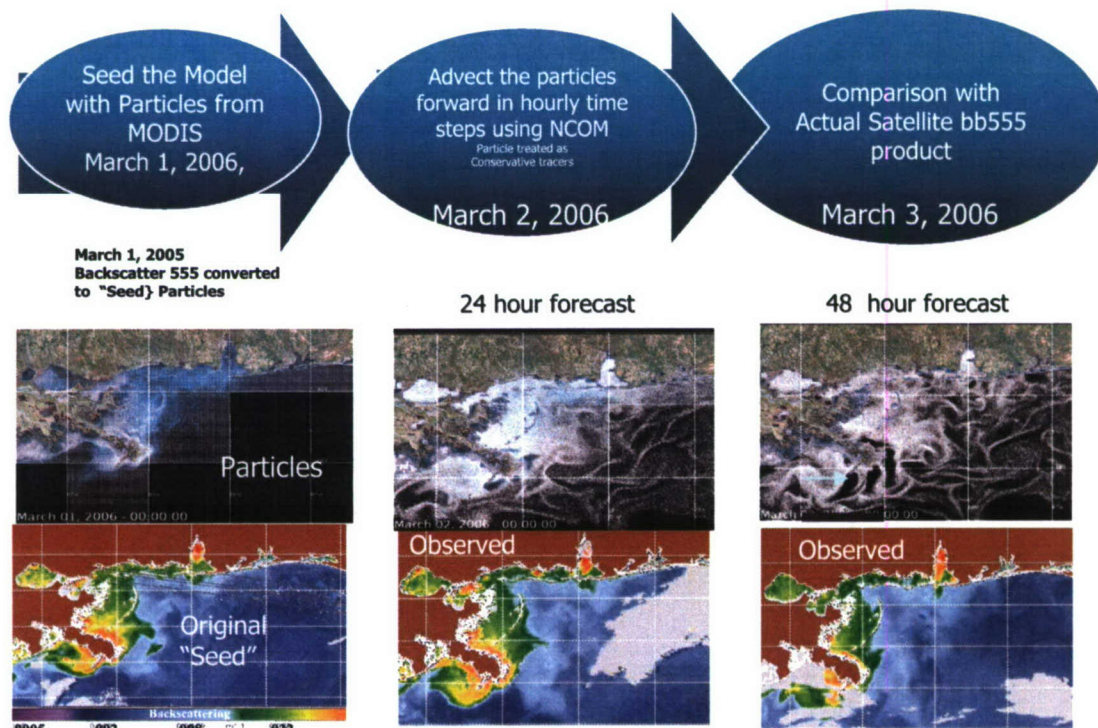


Figure 4. The MODIS backscattering product is used to "Seed" the surface model. The particles are forecast 24 and 48 hourly and then accumulated into a forecast bb555 image. The forecast are compared with the next day MODIS bb555 imagery to confirm errors.

Present issues with the forecast capability are linked to: 1) the initial seed field 2) inaccuracies with the coastal inputs (rivers etc.) 3) surface convergence and divergence fields. The errors in the initial seed field are associated with non-

complete satellite coverage from clouds etc. These non-complete particle coverage results in particle void regions which are advected in the forecast. These “voids” regions are presently being filled using a triangular bb55 interpolation procedure¹² which provides a method to initialize with complete coverage.

Similar problems with particle void areas occur when as particles are removed with no replacement. These areas are evident at river mouths where the initialized particle field is advected away from the source leaving a void (see Figure 4 –Arrow pointing to River plume). As these particle void areas is generated, they are observed emanating along coastal areas. These are can / should be filed as either point source particle field (i.e. River particle flux) or upwelled particles. (This river flux was filled in Figure 5.)

An example of the Mississippi River plume dispersion on to the Northern Gulf of Mexico is shown for April 23,2007 and forecasting April 24, 2007.

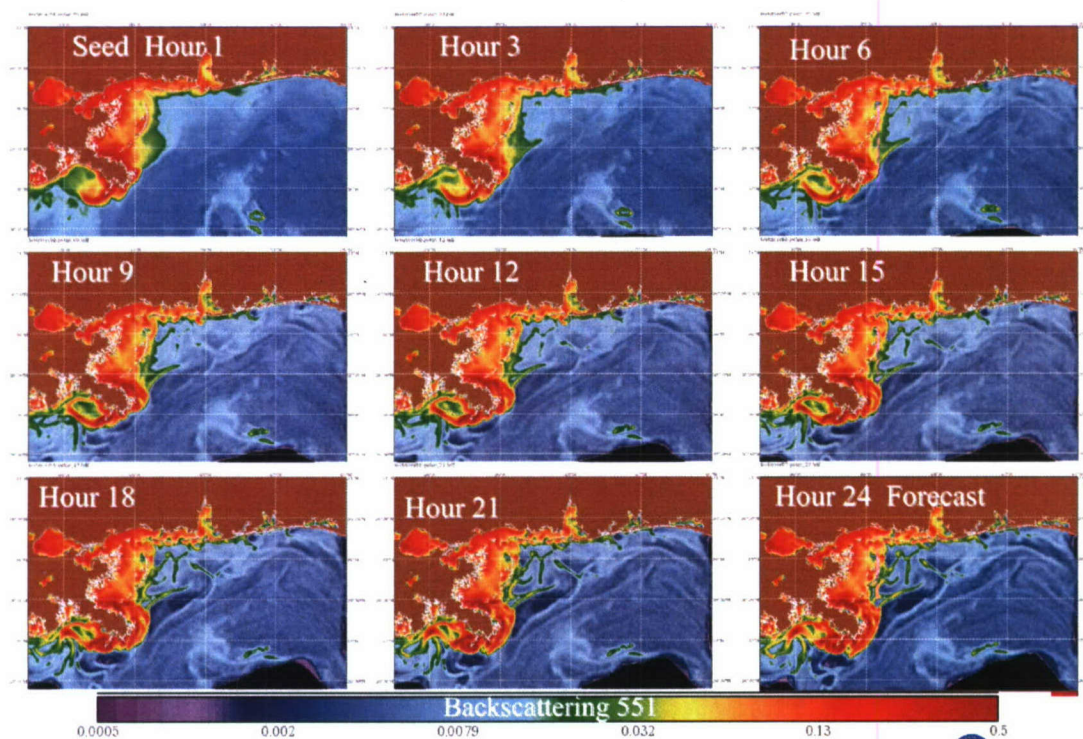


Figure 5. Forecast of the surface backscattering image from the MODIS particle “Seed” Field (hour 1). The 24 hour forecast of the particle field shows the change in MS river plume.

4. CONCLUSIONS

Ocean color imagery provides a realistic observation of the ocean surface optical properties but only to a depth of approximately 1 optical depth. Optical layers many times extend beyond the satellite penetration depth and are significant different than those observed at the surface. To provide a more complete 3-d realization of the ocean bio-optical properties, we have demonstrated a method to couple these surface satellite observations with physical properties from ocean models to extend the surface optics. The procedure is based on a characterizing the shape of a Gaussian vertical profile based on the interaction of the mixed layer depth, intensity of the mixed layer, 1 percent light level and the surface satellite chlorophyll. The method used observation such as gliders to help define the coefficients which

describe the Gaussian. The example of the 3-d profile is for the Northern Gulf of Mexico, however, the methods has been applied to other areas. The methods have been evaluated with insitu observations with reasonable results.

The forecasting of the coastal optical properties was demonstrated by “seeding” a coastal circulation model with the surface particle distribution and concentration based on MODIS satellite derived backscattering coefficients using the QAA algorithm^{13,14}. The intensity of the backscattering coefficient (bb551) was used to determine the particle concentration. This particle field was advected on hourly time steps using the NCOM circulation model using a fixed dispersion and particle settling term. The forecast particle field was accumulated and inverted back to the backscattering coefficient and compared with the next day MODIS backscattering image. The difference field of the forecast and satellite image provide a method to confirm the physical circulation field. These differences additionally illustrate that simple particle advection accounts for a large portion of the coastal bio-geo-optical processes occurring with 24 hours. However, the difference image can be used to identify other bio-optical processes such as phytoplankton growth, particle upwelling and downwelling, and particle fluxes associated with bottom resuspension and accumulation.

We provide an initial effort to demonstrate the integrated use of satellite bio-optical products, numerical circulation models and insitu observations for monitoring coastal processes and provide a forecast capability.

5. ACKNOWLEDEMENTS

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REFERENCES

- ¹ Arnone, R.A., B. Casey, D. Ko, J. Jollif, S. Ladner, and R. Gould. Defining the Bio-Optical Vertical Structure and Shelf Exchange Using Ocean Color Combined with Numerical Models. AGU/ASLO/TOS Ocean Sciences Meeting, Honolulu, HI, 20-24 February 2006
- ² Arnone, R.A. and A. R. Parsons,. “Real-time use of ocean color remote sensing for coastal monitoring.” in *Remote Sensing of the Coastal Environments*, Springer Publishing – , Chapter 14. eds. Richard L. Miller, Carlos E. Del Castillo, Brent A. McKee, Kluwer academic. 2004
- ³ Arnone, R., P. Flynn, D. S. Ko, P. Martinolich, R. Gould, and V. Haltrin. Forecasting Optical Properties from Satellite Derived Optical Properties. Proceedings, Ocean Optics XVIII, Montreal, Canada, 9-13 October, 2006
- ⁴ Lee, Z. Carder., K.L and Arnone., R.A. Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters “ Applied Optics Vol 41 No27 Sept 2002. p 5755-5772
- ⁵ Haltrin, V.I, and R.A. Arnone “An algorithm to estimate concentrations of suspended particles in seawater from satellite optical images “ Proceeding of the 2nd inter. Conference “Optical if natural Water” St. Petersburg Russia p71 – 76 ONW’2002 ed. Levin, and Gilbert. Aug. 2003
- ⁶ Lewis, M.R., J.J. Cullen, T. Platt.. Phytoplankton and thermal structure in the upper ocean – Consequences of non-uniformity in chlorophyll profile. Journal of Geophysical Research. 88:2565-2570, 1983.
- ⁷ Lee, Z.P., A. Weidemann, J. Kindle, R. Arnone, K.L. Carder, C. Davis, “Euphotic zone depth: Its derivation and implication to ocean-color remote sensing,” J. Geophys. Res., 2006
- ⁸ Martin, P.J.. A description of the Navy Coastal Ocean Model Version 1.0. NRL Report: NRL/FR/7322-009962. 39 p. 2000
- ⁹ Ko, Dong S., R.H. Preller, and P. J. Martin.. An Experimental Real time Intra Americas Sea Ocean Nowcast/Forecast System for Coastal Prediction. AMS 5th Conference on Coastal Atmospheric & Oceanic Prediction & Processes. 2003
- ¹⁰ Lee, Z. P., K.P. Du, R. Arnone, S.C. Liew, B. Penta, “Penetration of solar radiation in the upper ocean – A numerical model for oceanic and coastal waters,” J. Geophys. Res., 110, C09019, doi:10.1029/2004JC002780, 2005
- ¹¹ Arnone, R.A., H. Loise, K. Carder, E. Boss, S. Maritorena, Z.P. Lee; “Examples of IOP Applications” Chapter 13 in *Remote Sensing of Inherent Optical Properties: Fundamental, Test of Algorithms and Applications*. Reports of the International Ocean-Colour Coordinating Group, IOCCG In Press. Editors Z.P Lee. 2006

¹² Casey, B. and R.A. Arnone "Simple and efficient technique for spatial and temporal composite imagery", SPIE Optics and Photonics, Conference 6680-43, San Diego Aug 28-30 2007

¹³ Lee, Z., K.L. Carder, and R.A. Arnone.. Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters. *Applied Optics*. 41(27): 5755-5772. 2002

¹⁴ Lee, ZhongPing, K. Carder, R. Arnone "The Quasi-Analytical Algorithm" Chapter 10 in *Remote Sensing of Inherent Optical Properties: Fundamental, Test of Algorithms and Applications*. Reports of the International Ocean-Colour Coordinating Group, IOCCG In Press. Editors Z.P Lee. 2006